

Design and implementation of microstrip rotman lens for ISM band applications

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ABSTRACT

This work presents the design and implementation of Rotman lens as a beam steering device for Industrial, Scientific, and Medical (ISM) applications. 2.45 GHz is considered as a center frequency design with (2-6) GHz frequency bandwidth. The beam steering is examined to cover $\pm 21^\circ$ scan angle with maximum main lobe magnitude 10.1 dBi, rectangular patch antennas are used as radiation elements to beam the output far field. The work is extended to compare between the tapered line which is used for matching between 50- Ω ports and lens cavity. CST microwave simulation studio results show that the rectangular taper line can yield 2 dB return loss less than linear taper line with a little bit shifting in responses for same input and load impedance.

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1. INTRODUCTION

Rotman lens is a structure capable to produce multi-beam with different scan angle which is modelled depends on the geometric optics as shown in Figure 1. The first Rotman lens was firstly introduced by Rotman and Turner [1] with three focal points have theoretically zero phase error along the array front. The need for increase non-focal lens encourage many researchers to increase the number of focal points to four focal points in Quadru-Focal lens [2, 3] and the non-focal lens which have minimum average phase error for all radiation elements rather than achieve zero phase error for only selected elements have been reported in [4-6].

Low phase error, wide bandwidth, easy to fabricate in microstrip model, and True Time Delay (TTD) are main advantages of the lens compared with other beam forming technique as Butler matrix and Blass matrix [7]. Many military and commercial applications depend on the scanning of the desired angle based on Rotman lens. Radar sensing for the automotive system [8], indoor communication system [9] and mobile satellite communication [10] are applications used Rotman lens for switching the output beam.

In this study, a microstrip Rotman lens beam forming is designed for ISM applications with 2.45 GHz consider as a center frequency. CST microwave simulation studio is used to test the performance of the lens, in terms of input ports, return loss and coupling between beam ports and array ports. A rectangular patch antenna is used as an array element in order to realize the beamforming and the scan angle besides the far field performance. The work is extended to explain the matching technique used for match between lens cavity and 50- Ω ports.

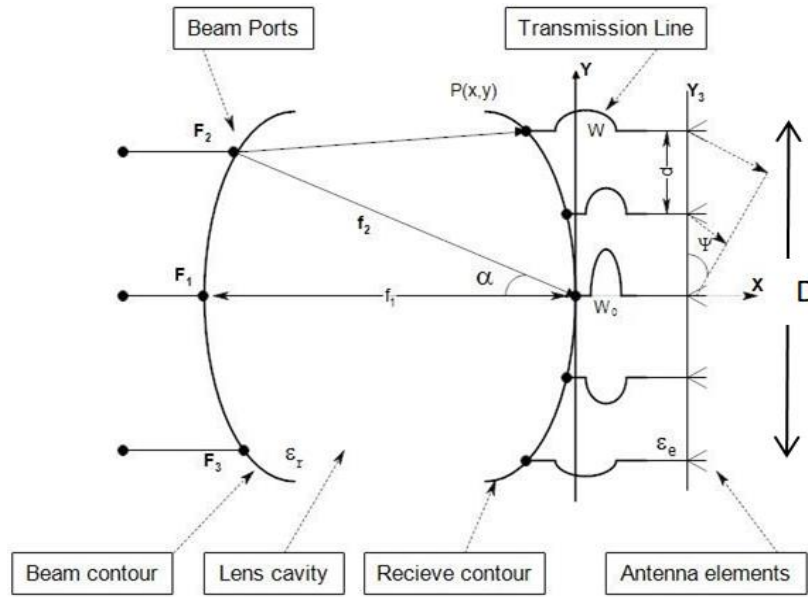


Figure 1. Rotman lens geometry [1]

2. RESEARCH METHOD

This section will be classified into three subsections. In the first section structure of the lens besides the design equations will be explained. While in the second section the antenna design will be explained. Finally, the third section will include the final prototype of the lens and the radiation elements.

2.1. Rotman lens model

The lens structure can be classified into three parts: The input part, side part, and the output part. The input part of the lens is a multi-ports arc including points located at beam contour. The beam contour can be designed as a circular or elliptical shape in order to reduce the phase error in some lens geometry [11]. At this point, it can be indicated that the number of the input ports control the number of the output beam on other terms, the number of the switching to scan the desired angle. Besides, the location of the beam ports related to scanning angle. The second part is the output part that included the receiver contour which contains the location points $P(X,Y)$ connected between the lens cavity and radiated elements through a transmission line with a length (W) in order to control the phase reached to the array elements. The sides of the lens covered with the side-wall which is connected to the ports terminated with $50\text{-}\Omega$ matched load in order to reduce the inside reflections in the cavity, that has a direct effect on the phase performance. The design of the side wall depends on the optimization process while the beam contour, the receiving contour, and the transmission line length can be calculated depend following equations derived from the geometric optics theory. Points located in the receiver contour $P(X,Y)$ and the transmission line length (W) can be determined by equalizing the path from the ideal focal points in beam countour to a related locations in the phase front. The normalized x , y and w to on-focal length can be determined from the following equations [12]:

$$w = \frac{\sqrt{\epsilon_e} - b \pm \sqrt{b^2 - 4ac}}{2a\sqrt{\epsilon_r}} \quad (1)$$

$$x = \frac{Y_3^2 \sin^2 \psi}{2\epsilon_r(\beta \cos \alpha - 1)} + \frac{(1-\beta)w}{\beta \cos \alpha - 1} \sqrt{\frac{\epsilon_e}{\epsilon_r}} \quad (2)$$

$$y = \frac{Y_3 \sin \psi}{\sqrt{\epsilon_r} f_1 \sin \alpha} \left(1 - \frac{w \sqrt{\epsilon_e}}{\beta \sqrt{\epsilon_r}}\right) \quad (3)$$

where; $a = 1 - \left(\frac{1-\beta}{1-\beta C}\right)^2 - \frac{\zeta^2}{\beta^2 \epsilon_r}$

$$b = -2 + \frac{2\zeta^2}{\beta \epsilon_r} + \frac{2(1-\beta)}{1-\beta C} - \frac{\zeta^2 \zeta^2 (1-\beta)}{(1-\beta C)^2 \epsilon_r}$$

$$c = \left(-\zeta^2 + \frac{\zeta^2 S^2}{1-\beta C} - \frac{\zeta^2 S^2}{1-\beta C} - \frac{\zeta^2 S^2}{4(1-\beta C)} \right) \frac{1}{\varepsilon_r} \zeta$$

$$\beta = \frac{f_2}{f_1}, \zeta = \frac{Y_3 \sin \psi}{f_1 \sin \alpha}, S = \sin \alpha, C = \cos \alpha$$

The work in this study is suggested to have same permittivity substrate material in the lens cavity and transmission lines. The lens performance is carried out by using Microwave Simulation studio CST commercial software. The tabled variables are considered in the Rotman lens design.

Table 1. Micorstrip Rotman lens design parameters

Design variable	value	Design variable	value
No. of beam ports	5	focal length (f_1)	$2.527 \lambda_g$
No. of antenna ports	4	displacement distance (d)	$0.5 \lambda_0$
No. of dummy ports	10	substrate thickness	1.6 mm
scan angle (α)	$\pm 21^\circ$	length	369.5 mm
relative permittivity(ε_r)	4.3	width	273.43 mm
loss tangent	0.025	center frequency	2.45 GHz
copper thickness	0.035mm		

The CST lens model with tapered ports is shown in Figure 2. The linear taper is used to ensure smooth transition energy and reduce the return loss between the lens cavity and the 50- Ω ports. Linear tapering is the common technique is used with the lens because of easy for modeling and fabrication. However, there are many others techniques can be used to guarantee an acceptable energy transition such as triangular taper and exponential taper which are considered as a taper line transmission line that depends on the length and width of the taper in order to optimize the reflection coefficient, while the multi-section taper depends on the standing wave pattern to find the minimum return loss. The tapered line will be discussed in detail in the final section of this study. Besides, ten dummy ports are designed and connected to the side wall of the lens in order to eliminate the inside reflections inside the lens cavity which is effect directly on the lens performance. A lens with five input ports from (1-5), four output ports (6-9) and ten dummy ports connected to side wall numbered from (10-19).

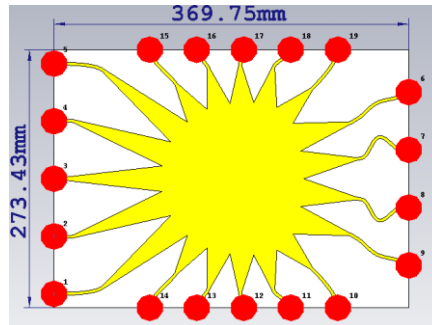


Figure 2. Rotman lens CST model

2.2. Rectangular patch antenna

A patch antenna is modelled and connected to the lens in order to realize the beam scan angle, design equations as reported in [13]. Figure 3 is a CST model patch antenna at center frequency 2.45 GHz with copper and substrate specification as mentioned in Table 1. Besides, two slots were added to the feed in order to enhance the return loss with the specified design frequency and its optimum dimension was achieved by using CST Nelder-Mead simplex optimization tool.

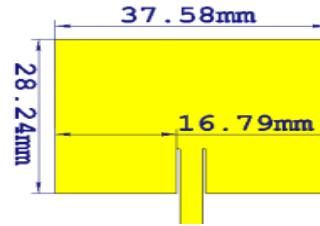


Figure 3. Rectangular patch antenna geometry

2.3. Lens with antenna geometry

The final geometry for the lens connected to the radiation elements is shown in Figure 4. Four rectangular patch elements connected to the output ports of the lens. The size of the geometry can be considered electrically large due to the center frequency of the lens design at 2.45 GHz with focal length $2.527 \lambda_g$. More optimization can be conducted in order to study the reduction of the focal length beside the taper line length and save the lens performance. In a practical system, one beam port will be excited at a single desired frequency in order to form the output beam. However, the desired direction of the scanning can be achieved by the switching between the input ports, on other terms every beam ports direct the output beam in a specific angle. So, as it is mentioned in the explanation of lens structure when the number of the beam ports increases this is lead to increasing of the scanning resolution of the lens. While the number of the output ports related to the number of the radiator elements which is effect directly with gain.

In the following sections, the simulation results of the lens performance such as beam ports return loss, the coupling between beam ports to receive ports, and the mutual coupling between beam ports will be explained. Besides the radiation element will be tested individually before connected it with lens. The work will be extending to cover matching types are used to balance impedance between lens structure and 50 Ω ports. Two types of taper line will be designed and compared in terms of return loss and dimensions.

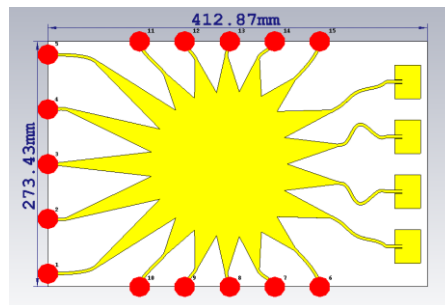


Figure 4. Rotman lens connected radiation elements geometry

3. RESULTS AND ANALYSIS

Experimental results can be classified into four subsections. In section one the results regarding lens performance in terms of coupling between ports, return loss, and phase performance will be explained. While in section two the results related to antenna parameters will be discussed. Then, the output far field of full geometry of the beam forming system including a lens and array elements will be described in section three. Finally, the matching techniques used for matching with lens cavity will be explained.

3.1. Lens simulation results

The full scatter matrix has been solved numerically with CST-MWS. The return loss for only three beams ports is shown in Figure 5 due to symmetrical geometry. It can be concluded from Figure 5 that Port 1 and port 2 have higher return loss due to its off-axis position on the band test. While the return loss for the port 3 has less return loss over the entire frequency range (2-6) GHz. The coupling between the beam ports and array ports can be explained the power transmitted from the beam ports to the array ports as explained in Figure 6 (a).

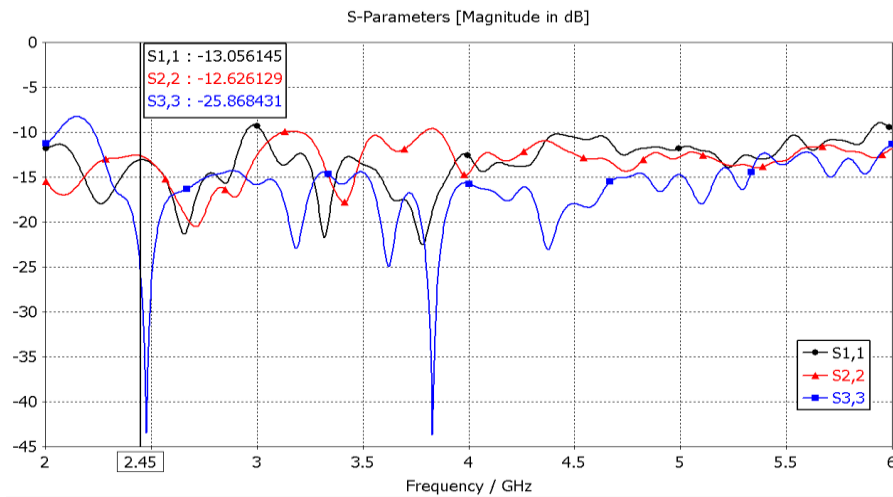
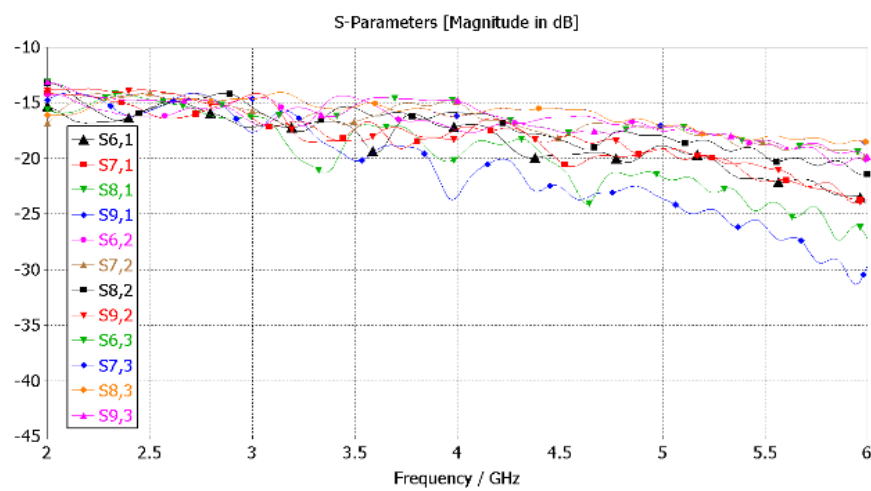
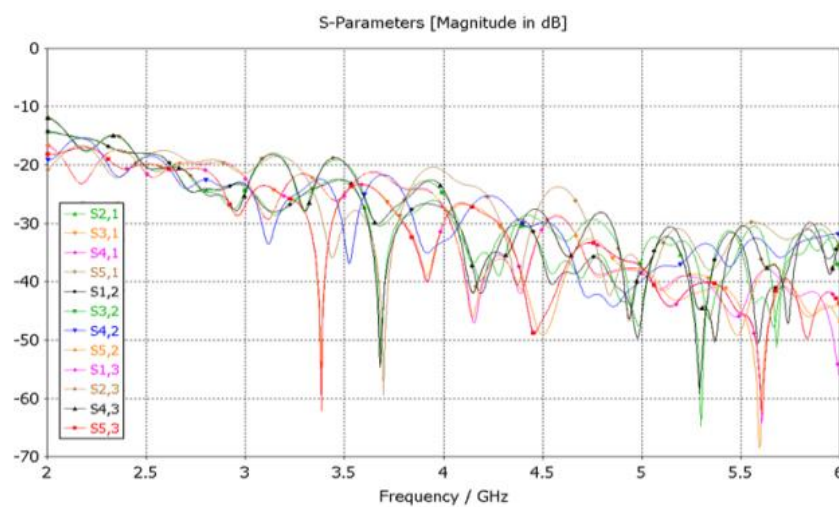


Figure 5. Return loss of beam ports



(a)



(b)

Figure 6. Simulated results of lens performance (a) Coupling between beam ports and array ports (b) Mutual coupling between beam ports

It observed that acceptable power under -10 dB is transmitted from the beam ports to array ports and the average fluctuation is between -13 dB to -17 dB at 2.45 GHz that indicate almost even power received to all array ports. The interaction between adjacent input ports considered as an important factor in terms of power loss and can be observed as a mutual coupling between ports as shown in Figure 6 (b). The spacing between adjacent input ports has the main effect on the interaction between ports. Generally, an acceptable isolation was observed in the test band. Besides, at the frequency of interest 2.45 GHz the mutual coupling has the values between -18 dB and -22.61 dB which is make a good indication for power isolation.

The phase performance of the lens is described in the Figure 7 in terms of electric field distribution when port 3 is excited with 2.45 GHz and all others ports are terminated with 50- Ω loads. Phase observation without any distortion can be noticed over the entire lens surface. Besides, there is a good absorption from the side wall tapering line without inside reflections.

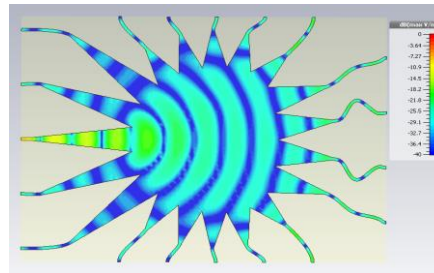


Figure 7. Electric field distribution through Rotman lens

3.2. Antenna simulation results

The return loss is -24.79 dB at 2.45 GHz with 85.2 MHz bandwidth as shown in Figure 8 (a). The far field for the patch antenna is shown in Figure 8 (b). A better performance for the gain 6.24 dBi can be observed at 2.45 GHz with side lobe level -8.9 dB.

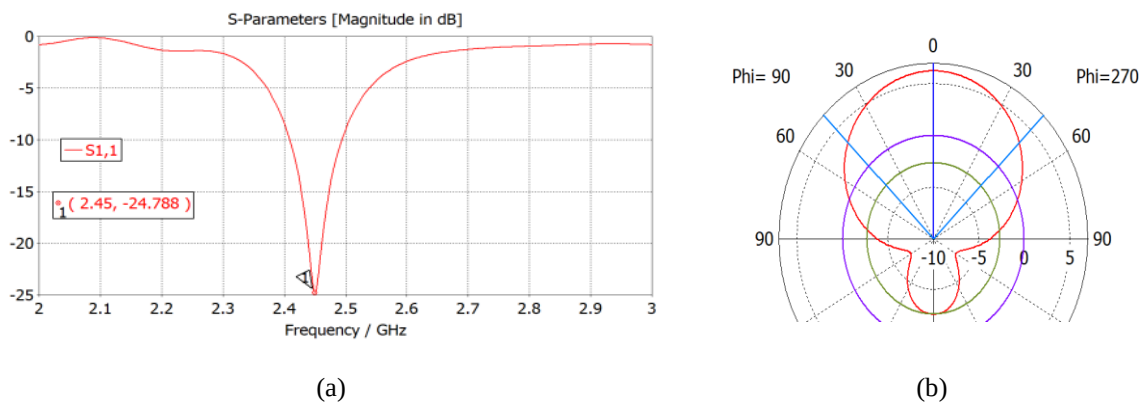


Figure 8. Simulated results of antenna performance (a) Return loss of patch antenna (b) Directivity pattern of rectangular patch antenna

3.3. Lens with antenna simulation results

The polar beam forming plot for the lens shown in Figure 9 when excited the beam ports with 2.45 GHz and load the others ports with 50- Ω in order to absorb the incident energy. The five far filed switched from $+21^\circ$ to -21° with fluctuation in the amplitude about 1 dBi due to higher side lobe level equal to -11.6 dB when port 1 and port 5 are excited. Besides, the maximum directivity is 10.1 dBi when port 3 is excited with -12.1 dB sidelobe level.

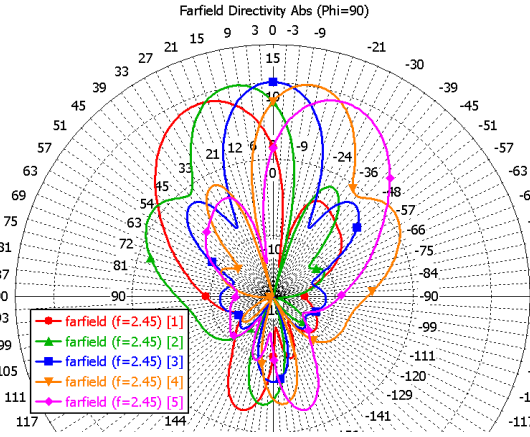


Figure 9. Radiation pattern beams for Rotman lens with antenna

3.4. Tapered line for impedance matching

The matching impedance between lens ports and its cavity is considered very important in terms of lens performance; because it is directly related to energy saving, bandwidth and phase performance. The traditional technique for matching used in the lens is a linear tapered line for simplicity and ease of fabrication as Figure 10 (a) explained its dimensions, in order to ensure smooth energy transformation from the 50-Ω ports to the lens cavity.

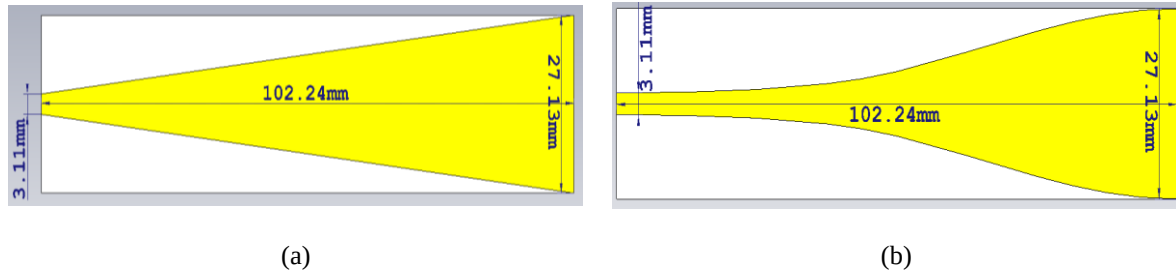


Figure 10. (a) Linear taper CST model. (b) Triangular taper CST model

The linear taper can be modelled by applying (4) [14]:

$$Z(z) = Z_0 z + s \quad 0 < z < L, s \neq 0 \quad (4)$$

The input characteristic impedance is calculated with same variables as mentioned in Table 1. The load impedance is suggested in Figure 10 and the length (L) is optimized in order to achieve acceptable return loss using CST Nelder-Mead simplex method optimization. The triangular taper line can be modeled using (5) [14]:

$$Z(z) = \begin{cases} Z_0 e^{2(z/L)^2 \ln Z_L/Z_0} & 0 \leq z \leq L/2 \\ Z_0 e^{(4z/L - 2z^2/L^2 - 1) \ln Z_L/Z_0} & L/2 \leq z \leq L \end{cases} \quad (5)$$

The CST triangular taper line with same design parameters as linear taper is shown in Figure 10 (b). CST simulation return loss result of both taper lines within the range of (2-6) GHz is described in Figure 11.

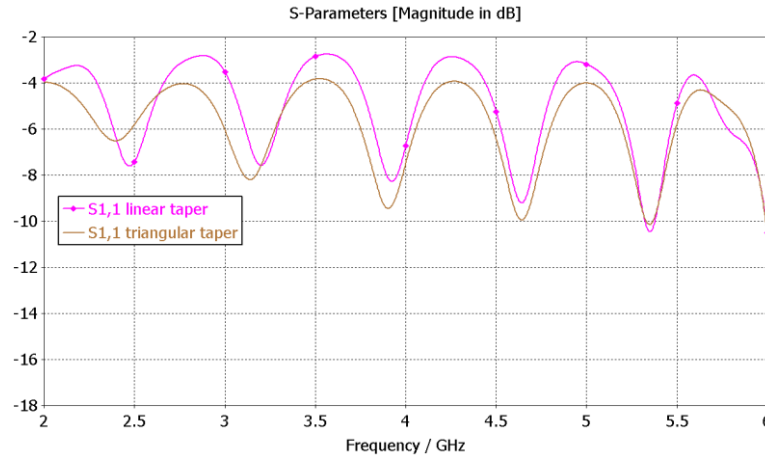


Figure 11. Return loss of linear and triangular taper

The result observed the different response in the test band (2- 6) GHz. The triangular taper line can be yield a return loss less than linear taper line with a small shifting. On another hand, a multi-section feeding technique can be applied to the lens suggested it as parallel plate region depending on the standing wave pattern as reported in [15].

4. CONCLUSION

Rotman lens with five beam ports and four output ports is designed and modeled for ISM applications with bandwidth (2-6) GHz. Coverage scan angle from $+21^\circ$ to -21° is achieved by using rectangular patch antenna as radiated elements with maximum gain 10.1 dBi. The matching techniques used in Rotman lens was tested by using two types of tapered line. The simulated results explained different return loss with the same design specification. On the other hand, the triangular tapered line can be yield less return loss than the linear taper line with a maximum difference 2 dB in the test range (2-6) GHz.

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